A Personal Experience of Using Computer Technology to Assist with the Treatment of Diabetes

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Abstract: Computer systems have been shown to be useful in the task of diabetes care. This article describes a computer system based on a mathematical model developed for personal use by a type I diabetic to assist with the task of blood glucose control.

Keywords: Diabetes. Mathematical Models. Medical Applications.

1. INTRODUCTION

Insulin Dependent Diabetes Mellitus needs to be treated with insulin injections and a controlled diet to keep blood glucose levels within the required range. The development of the home blood glucose monitoring device has made this task much easier, as these devices allow the blood glucose level to be measured a number of times a day, instead of at the clinic once every few months, as was the case in the old days.

A number of computer systems have been developed which make use of Self-Monitored Blood Glucose (SMBG) values to provide therapy adjustment decision support. Some of these systems have been shown to improve outcomes. See Schiffrin et al. (1985), Cavan et al. (1998) and Albisser et al. (2007) for some examples.

I have had insulin dependent diabetes since August 1969. I was on a single daily dose of long acting insulin from the time I was diagnosed until 1985. During that period, my control was assessed by checking for urine glucose, avoidance of hypoglycaemic events, and infrequent random blood glucose checks.

In August 1985, my GP suggested that I purchase a home blood glucose testing machine, and referred me to a diabetes specialist. Under the care of the diabetes specialist, I started to monitor my blood glucose levels, and changed from a single daily dose to a basal/bolus regime of a long acting dose of Ultratard plus three meal time short acting doses of Actrapid.

According to Tattersall (1977), the term Brittle Diabetes is applied to cases where frequent and rapid changes between high and low blood glucose levels are often seen, and these changes are often hard to explain. The description *Brittle* refers to the idea that the control is so fragile that it is easily broken. I do experience rapid and frequent fluctuations in blood glucose level, often with no easy to see cause, and hence can be considered to come into the category of Brittle Diabetes. Table 1 and Table 2 show some blood glucose values from days with large fluctuations.

Table 1. Blood Glucose Readings on Monday 8th July 2002

Time	Reading (mg/dl)	(MMol per Litre)
00h24	117mg/dl	6.5 mmol/l
07h58	314mg/dl	17.4 mmol/l
09h28	220mg/dl	12.2 mmol/l
10h28	164mg/dl	9.1 mmol/l
13h24	123mg/dl	6.8 mmol/l
16h56	327mg/dl	18.2 mmol/l
18h42	221mg/dl	12.3 mmol/l
21h06	76mg/dl	4.2 mmol/l
23h01	58mg/dl	3.2 mmol/l

Table 2. Blood Glucose Readings on Tuesday 22nd December 2009

Time	Reading (mg/dl)	(MMol per Litre)
00h15	185mg/dl	10.3 mmol/l
08h33	266mg/dl	14.8 mmol/l
10h47	283mg/dl	15.7 mmol/l
12h36	337mg/dl	18.7 mmol/l
19h27	65mg/dl	3.6 mmol/l
23h48	212mg/dl	11.8 mmol/l

2. FORMULATING THE MATHEMATICS

Towards the end of 1986, I was thinking about how I might be able to use numerical methods and a computer to optimise blood glucose control.

I began to construct a mathematical model which could use measurements of insulin dosage, food intake, and the blood glucose readings, to give an approximate value for blood glucose at any time between the actual readings.

I used the following formula to extrapolate blood glucose value at time t from a blood glucose reading at time 0 :

$$G(t) = \int_0^t G(0) - I(t) + F(t) - E(t) + H(t) + V(t)dt \quad (1)$$

where

I(t) is the effect of insulin
F(t) is the effect of food
E(t) is the effect of exercise

H(t) is glucose production in the liver
V(t) represents various other factors, both positive and negative, including the Dawn Effect and excretion of glucose by the kidneys

I needed to define functions for insulin injections, food, exercise, and the other factors, describing their effect on blood glucose level over time. After some consideration, I decided to use sine waves to approximate most of these functions.

The starting point was to define a function for insulin action, based on the time action charts from Novo Nordisk. Initially, I used

$$I(t) = Q\sin(\frac{\pi}{P}t)\ 0 < t < P \tag{2}$$

where P is the period of action and Q is a parameter to adjust the magnitude of the peak.

This gives a single sine wave peak, with duration P, and gives a value for insulin action for t from 0 to the end of the dose action period.

This function was constructed such that the integral of the function over its period of action had the numerical value of 10. A value of 10 was chosen, as I expected that the change in blood glucose level due to a dose of one unit of insulin would be of the order of magnitude of 10 mg/dl. The value of the function was then multiplied by a factor to translate it into a value of resultant change in blood glucose level. This number, *ip*, the insulin parameter, is a model parameter, and was determined by taking some blood glucose measurements after injecting a dose of insulin.

Thus, the term within the model for calculating the effect of insulin on blood glucose is:

$$I(t) = ip(Q\sin(\frac{\pi}{P}t))\ 0 < t < P \tag{3}$$

The different types of insulin were represented by using different values of P and Q. All of the other functions and calculations were then based on the values of the insulin functions.

The food functions are similar to the insulin ones. Each is represented by a sine wave, with different periods of action for the different types of food, and having an integral value over the period of action of 10 for 100 kcal of energy content.

The food equation is:

$$F(t) = Q\sin(\frac{\pi}{P}t)\ 0 < t < P \tag{4}$$

As with the insulin functions, the value of the function is multiplied by a food parameter to adjust it. This value, *fp*, was again found by experimentation. As with the insulin functions, the magnitude value in the equation, Q, is multiplied by this fp parameter to adjust the effect of food on the blood glucose value.

Exercise is simply a constant value which indicates the level of the exercise being undertaken over the period of the activity.

$$E(t) = L \tag{5}$$

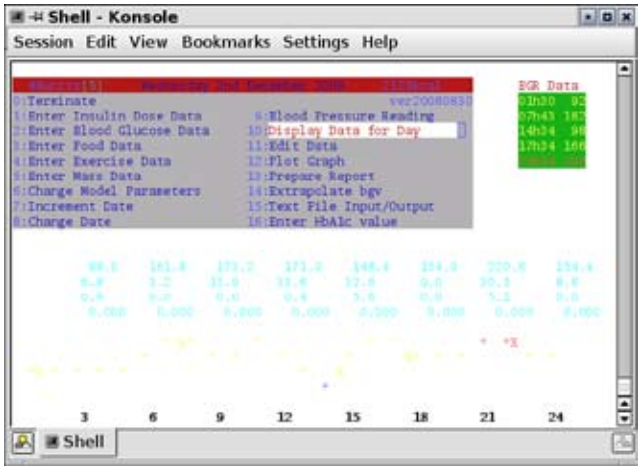

Fig. 1. Screen Shot with BG Level Extrapolation

for t within the period of exercise.

H(t) is a function which produces an increase in blood glucose levels when blood glucose and insulin levels are both low, as glucose production by the liver is inhibited by both higher levels of insulin and glucose in the blood.

V(t) contains elements which decrease the blood glucose level when it is high to account for glucose excretion by the kidneys, and decrease insulin action in the early morning to implement the dawn effect.

After formulating a mathematical representation for blood glucose extrapolation, I developed a Pascal program to collect the required information and implement the model.

3. FUNCTIONS OF THE SYSTEM

Information about insulin doses, food eaten, blood glucose readings and other health related data can be entered into the system.

The program interface is text based, as shown in Fig. 1, as it was developed before GUI operating system user interfaces and applications became the standard.

The screen has a menu of options for entering data, extrapolating blood glucose, plotting graphs, and producing reports.

A bar at the top of the screen displays the current date as well as the totals of insulin doses (total number of units, and number of doses), as shown in Fig. 2 and food intake for the current day (total calories). Under this bar is the menu section. On the right hand side, a list of blood glucose readings for the day is displayed, colour coded according to whether they are in or out of range (Fig. 3 and Fig. 4). Values that are within the desired range are yellow, while those that are too low are displayed in blue, and red indicates too high.

The bottom half of the screen is used for data entry and displaying information.

3.1 Blood Glucose Level Extrapolation

Using the last blood glucose reading and information about insulin doses, exercise undertaken, and food eaten,

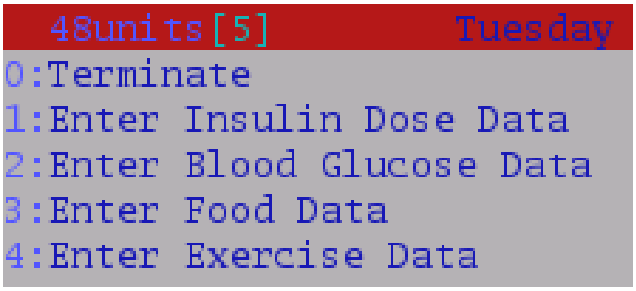

Fig. 2. Total Insulin Dosage

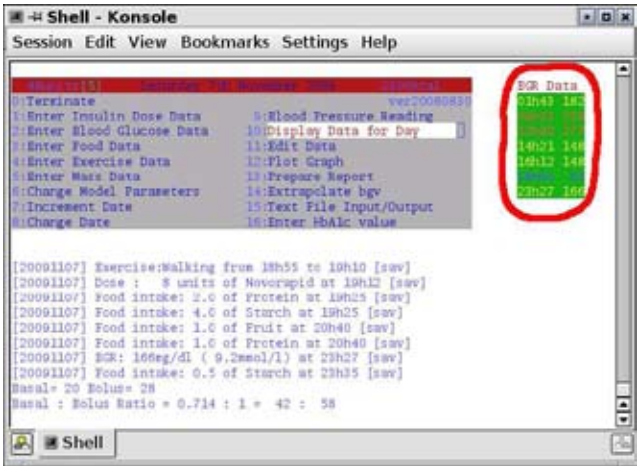

Fig. 3. Blood Glucose Readings Section Highlighted

Fig. 4. List of Colour Coded Blood Glucose Readings

the program can work out an approximation of how the blood glucose will change over time.

A graph can be produced showing a plot of insulin and food action, blood glucose readings, and the estimated blood glucose fluctuation over the period of a day, as shown in Fig. 5.

Data items and blood glucose extrapolation is handled with respect to a single day, from midnight (00:00) to 23:59. No features to handle changes in time due to daylight saving or travelling between different time zones

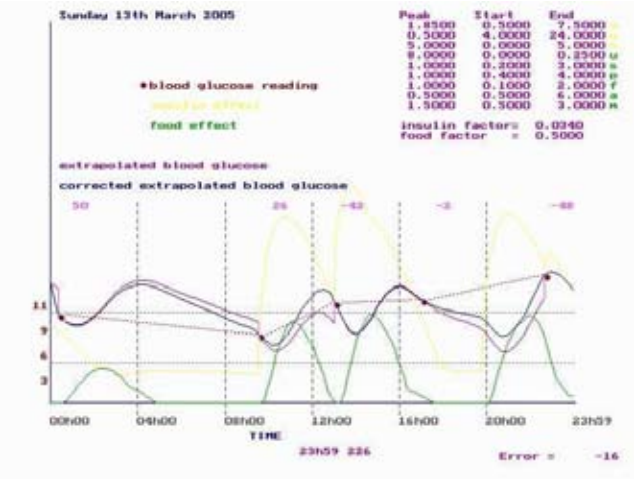

Fig. 5. Graphic Output:Extrapolated Blood Glucose Level

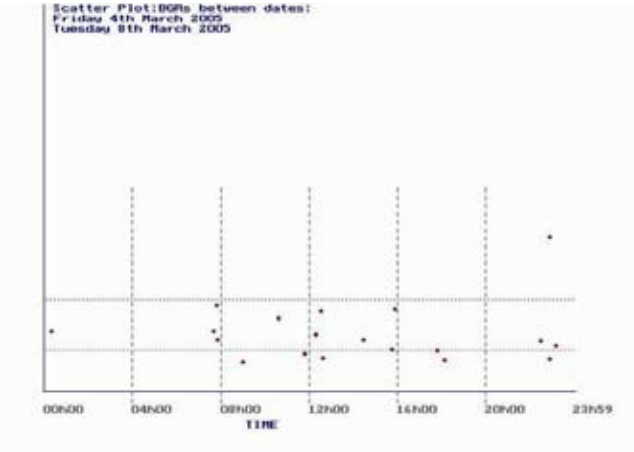

Fig. 6. Scatter Plot

have been implemented. Thus, trying to keep track of the information relating to a day spent travelling from Auckland to Los Angeles is difficult, and any resulting calculations will be very inaccurate.

3.2 Data Reporting

A scatter plot can be produced to show the variation of blood glucose readings at different times over a number of days. (Fig. 6) This is useful, as superimposing readings from a number of days can show trends in blood glucose during the course of a day. It also gives a visual indication of the spread of the values. A wide vertical spread shows instability in blood glucose control, while closely grouped points are more desirable.

Data entered into the system can be output in the format of a report, suitable for presentation at clinics.

Example of report output:

```
04h16:Glucose value of  220mg/dl recorded (12.2 mmol/l)
04h17:  2 units of Novorapid taken
07h21:Glucose value of  144mg/dl recorded (8.0 mmol/l)
07h40: 10 units of Novorapid taken
 Food intake: 3.0 of Starch at 07h48
 Food intake: 1.0 of Fruit at 07h48
 Food intake: 1.0 of Milk at 07h48
```

```
08h40:  5 units of Protaphane taken
 Food intake: 1.0 of Starch at 10h00
12h23:Glucose value of   84mg/dl recorded (4.7 mmol/l)
13h30:  8 units of Novorapid taken
 Food intake: 6.0 of Starch at 13h32
 Food intake: 1.0 of Fruit at 13h32
 Food intake: 1.0 of Protein at 13h32
18h57:  8 units of Novorapid taken
 Food intake: 1.0 of Fat at 19h15
 Food intake: 2.0 of Protein at 19h15
 Food intake: 5.0 of Starch at 19h15
 Food intake: 1.0 of Fruit at 20h45
22h16:Glucose value of  121mg/dl recorded (6.7 mmol/l)
22h17: 10 units of Ultratard taken
 Food intake: 1.0 of Protein at 22h30
 Food intake: 1.0 of Fruit at 22h30
 Food intake: 1.0 of Starch at 22h40
```

4. MODEL ACCURACY

4.1 Differences Between Actual and Predicted Values

This section is an analysis of blood glucose values predicted by the model at a given time, compared to values of actual blood glucose readings at the same time. The readings have been put into the three categories of below acceptable, within desired range, and too high. In the output below, the symbols used to categorise the values are "-" to show too low, "*" for in range, and "+" for too high. The two symbols at the end of the line show the categories of the actual and predicted values. If they are both the same, then the prediction is counted as being a "good prediction", where the actual and predicted values are both in the same category. The final lines show the numbers for where they match, or the predicted value is in a range above or below the real value. In the example data used here, they matched in 20 out of 33 cases. Thus, more than half (60%) of the predictions were good enough to be clinically useful.

The"Total Error for Day" just adds up the errors. If there are a number of readings in the day, and if there are inaccuracies in absorption timings in the functions, then the actual rate of change of blood glucose level will be different to that shown by the model. If there are differences along the way, but they both get to a similar value in the end, then the errors will cancel each other out. The "Average Error for Day" is the total error divided by the number of readings in the day.

Example Data Set: Values for February 2010: Values are expressed in mg per dl.

```
20100201
07h14: Actual Value:303  Predicted Value: 175  Error:  -128  +*
11h27: Actual Value:146  Predicted Value: 262  Error:  116  *+
16h28: Actual Value:184  Predicted Value: 135  Error:  -49  **
22h33: Actual Value:139  Predicted Value: 156  Error:  17  **
Total Error for Day=  -44
Average Error for Day=-11.00

20100202
01h46: Actual Value:196  Predicted Value: 177  Error:  -19  **
07h18: Actual Value:385  Predicted Value: 220  Error:  -165  ++
11h43: Actual Value:230  Predicted Value: 293  Error:  63  ++
16h16: Actual Value:128  Predicted Value: 247  Error:  119  *+
Total Error for Day=   -2
Average Error for Day= -0.50

20100203
12h23: Actual Value:175  Predicted Value: 173  Error:  -2  **
23h23: Actual Value:229  Predicted Value: 110  Error:  -119  +*
Total Error for Day= -121
Average Error for Day=-60.50

20100204
07h42: Actual Value:213  Predicted Value: 206  Error:  -7  ++
12h38: Actual Value:106  Predicted Value: 143  Error:  37  **
18h45: Actual Value:  68  Predicted Value:  68  Error:  0  --
22h38: Actual Value:112  Predicted Value: 130  Error:  18  **
Total Error for Day=   48
Average Error for Day= 12.00

20100205
02h02: Actual Value:297  Predicted Value: 100  Error:  -197  +*
07h27: Actual Value:340  Predicted Value: 320  Error:  -20  ++
22h45: Actual Value:220  Predicted Value: 265  Error:  45  ++
Total Error for Day= -172
Average Error for Day=-57.33

20100206
07h51: Actual Value:297  Predicted Value: 172  Error:  -125  +*
11h15: Actual Value:232  Predicted Value: 244  Error:  12  ++
22h50: Actual Value:  83  Predicted Value: 190  Error:  107  **
Total Error for Day=   -6
Average Error for Day= -2.00

20100207
07h57: Actual Value:233  Predicted Value: 200  Error:  -33  ++
10h39: Actual Value:222  Predicted Value: 192  Error:  -30  +*
15h21: Actual Value:135  Predicted Value: 162  Error:  27  **
Total Error for Day=  -36
Average Error for Day=-12.00

20100208
00h11: Actual Value:245  Predicted Value: 170  Error:  -75  +*
11h05: Actual Value:  83  Predicted Value: 215  Error:  132  *+
22h40: Actual Value:248  Predicted Value:  57  Error:  -191  +-
Total Error for Day= -134
Average Error for Day=-44.67

20100209
02h36: Actual Value:198  Predicted Value: 223  Error:  25  *+
07h37: Actual Value:320  Predicted Value: 231  Error:  -89  ++
15h42: Actual Value:  96  Predicted Value: 266  Error:  170  *+
21h12: Actual Value:  94  Predicted Value:  48  Error:  -46  *-
Total Error for Day=   60
Average Error for Day= 15.00

20100210
07h01: Actual Value:221  Predicted Value: 236  Error:  15  ++
15h43: Actual Value:146  Predicted Value: 155  Error:  9  **
22h49: Actual Value:243  Predicted Value: 214  Error:  -29  ++
Total Error for Day=   -5
Average Error for Day= -1.67

Below:8
Same level:20
Above:5
```

4.2 HbA1c Estimates

In this test, results from the model were used to estimate HbA1c values. HbA1c results were compared with two different measures of average blood glucose levels. The average blood glucose value over the period of three months before an HbA1c test was calculated both as the mean of the test results recorded over the period, and as the mean of the average value of a blood glucose function for each day, calculated using the mathematical model.

The average value of a function f(x) between x = a and x = b is defined as:

$$Av = \frac{1}{b-a}\int_a^b f(x)dx \tag{6}$$

(Goodman. (1980))

This value was calculated for each day, with f(x) being G(t), the variation of blood glucose as calculated by the model for t from 00:00 to 23:59. This calculation gives a

Table 3. Blood Glucose Averages and HbA1c Results

AvBGV (mmol/l)	HbA1c(%)	CalcAv(mmol/l)
10.9	8	10.4
11.5	8	9.4
9.6	7.9	7.9
9.2	7.7	7.7
9.9	8.7	9.3
8.8	7.6	8.5
9.2	7.4	8.0
9	7.6	7.9
9.9	8.2	8.7
9.2	8.4	8.1
8.4	7.2	7.9
9.5	8.4	8.9
9.9	8.1	8.4
9.8	8	9.2
10.3	8.3	9.2

continuous average for the blood glucose level over the day. A value, CalcAv was calculated by averaging these results over a 90 day period, ending on the date of the HbA1c test, thus giving a continuous average estimate for the period.

$$CalcAv = \frac{1}{90} \sum_{day=1}^{90} Av_{day} \tag{7}$$

The value AvBGV is the average of the actual blood glucose test results during the same period.

$$AvBGV = \frac{1}{k} \sum_{i=1}^{k} bg_i \tag{8}$$

Averages using both methods were calculated from a set of data over a period which included 15 HbA1c tests.

4.3 Correlation of Values

The average of the $(AvBGV - HbA1c)$ value is 1.7, and the average of the $(AvBGV - CalcAv)$ value is 0.7. Thus, the values calculated using the average value of the model's calculated blood glucose function are seen to give a closer correlation with the HbA1c test results. One explanation for the average of the readings being higher than the actual blood glucose value is that the mean of the set of recorded blood glucose tests will often give a value on the high side, due to the fact that blood glucose sampling will tend to be done more often when values are running high. In the event of hypoglycaemic symptoms, the action taken will be to eat, rather than perform a blood test. Conversely, in the case of hyperglycaemic symptoms, the blood glucose level is likely to be checked before an extra dose of insulin is taken. A number of tests may then be performed, while the values are still high, while attempts are made to return the value to an acceptable level.

As HbA1c is considered to indicate average blood glucose value over a period of around three months (Rohlfing et al. (2002)), the correlation between the HbA1c readings and the model output do indicate that the extrapolated blood glucose variation produced by the model are a reasonable indication of the actual blood glucose values.

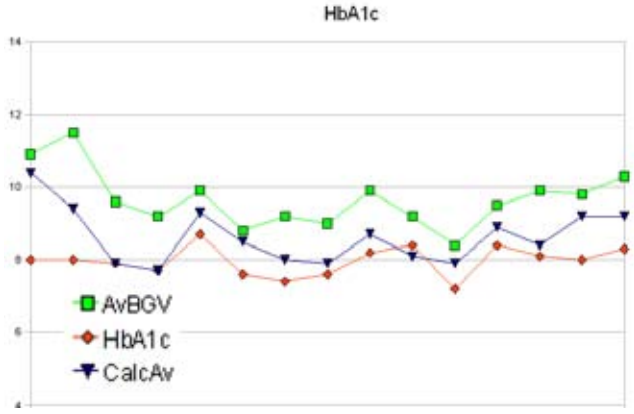

Fig. 7. Averages and HbA1c

5. CONCLUSION

The model predictions are accurate enough to make the system a useful tool. The model input data that is the most difficult to quantify accurately is food intake. Thus, this has the greatest impact on the accuracy of the predictions.

Storing and analysing data relevant to diabetes control aids overall treatment. Having self-monitored blood glucose values in an ordered and meaningful format at clinic visits greatly aids the process of evaluating and adjusting therapy. The patient is motivated to perform these tests accurately and frequently when it can be seen that the test results are being put to good use. These factors help to maintain the health of the diabetes patient.

The overheads in terms of data collection of the mathematical model approach are high, and limit the intensive use of this method. A large amount of data has to be collected and entered into the system, and it has to be accurate and complete for the system to be able to function as intended. Thus, it may not be suitable for all people, or for use all of the time by those who do choose to use it.

I have been using the system described here for more than 20 years, and I have found the system to be a very useful aid to assist with the control of my diabetes. While I often experience the wide ranging blood glucose levels of Brittle Diabetes, this instability would be much worse without the assistance provided by this program. I have had diabetes for over 40 years now, and am not suffering the effects of any serious complications.

This article describes one computer system to assist with the problem of blood glucose control in diabetes. A number of other systems have been developed which also use a mathematical model to extrapolate blood glucose values. These include DIAS (Cavan et al. (1996), Cavan et al. (1998)), AIDA (Lehmann and Deutsch (1996)), HumaLink (Albisser et al. (2007)) and Librae (Franklin et al. (2005)).

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